Integrated Pest Management Reviews **4:** 127–142, 1999.
© 1999 *Kluwer Academic Publishers. Printed in the Netherlands.*

Management of stored wheat insect pests in the USA*

David W. Hagstrum[1,**], Carl Reed[2] and Phil Kenkel[3]
[1]*USDA, ARS, Grain Marketing & Production Research Center, 1515 College Avenue, Manhattan, KS, USA;*
[2]*Department of Grain Science & Industry, Kansas State University, Manhattan, KS, USA;*
[3]*Department of Agricultural Economics, Oklahoma State University, Stillwater, OK, USA;*
[**]*Author for correspondence (Tel.: (785) 776-2718; Fax: (785) 776-2792; E-mail: hagstrum@usgmrl.ksu.edu)*

Received 28 May 1998; accepted 20 December 1999

Key words: wheat, stored-grain, integrated pest management, aeration, biological control, grain sampling, insect monitoring, modeling, area-wide IPM

Abstract

Management of stored-grain insect pests by farmers or elevator managers should be based upon a knowledge of the grain storage environment and the ecology of insect pests. Grain storage facilities and practices, geographical location, government policies, and marketing demands for grain quality are discussed as factors influencing stored-grain insect pest management decisions in the United States. Typical practices include a small number of grain samples designed to provide grain quality information for segregation, blending and marketing. This low sampling rate results in subjective evaluation and inconsistent penalties for insect-related quality factors. Information on the efficacy of insect pest management practices in the United States, mainly for farm-stored wheat, is discussed, and stored-grain integrated pest management (IPM) is compared to field-crop IPM. The transition from traditional stored-grain insect pest control to IPM will require greater emphasis on sampling to estimate insect densities, the development of sound economic thresholds and decision-making strategies, more selective use of pesticides, and greater use of nonchemical methods such as aeration. New developments in insect monitoring, predictive computer models, grain cooling by aeration, biological control, and fumigation are reviewed, their potential for improving insect pest management is discussed, and future research needs are examined.

Introduction

Management of insect pests by farmers or elevator managers should be based upon a knowledge of the grain storage environment and the ecology of insect pests. Wheat kernels remain on the plant for only a few weeks after they mature. However, the same seeds may spend several months or years in storage before being processed into food. During storage, seeds are vulnerable to attack by stored-product insects. Several cosmopolitan insect species are commonly found in stored-grain. The most damaging insect pests of stored wheat in the United States are the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), and the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) (Gundu Rao and Wilbur 1972, Bekon and Fleurat-Lessard 1992), because they consume significant portions of an infested kernel, deposit feces and cast skins, and can cause localized increases in heat and moisture that lead to accelerated mold growth. Cast larval head capsules and adult exoskeletons of internal-feeding insects leave fragments in flour when wheat is milled. Other insect species in the genera *Tribolium*, *Oryzaephilus*, *Cryptolestes*, *Ahasverus*, and *Typhaea* are commonly found in stored wheat (Pedersen 1992), but cause little damage to grain and contribute little to the insect fragment count in flour.

*This is Kansas Agricultural Experiment Station Contribution 98-462-J.

Insect infestations are common in farm-stored wheat in the United States. Storey et al. (1983) detected insects in about 1/4 of over 4,000 grain samples from wheat stored for 1–4 years on farms in several states, and the mean density in infested lots was 19 insects per kilogram of grain. More recent studies have shown that insect densities were lower when newly-harvested wheat was stored for less than a year (Hagstrum 1987, 1989). The ecology of stored-grain insect pests has been reviewed by Hagstrum and Flinn (1992), Hagstrum (1995) and Hagstrum et al. (1995).

Storage facilities

Wheat is stored in a network of facilities that encompasses the entire populated world. In the major wheat production areas in the United States, most farms have grain storage bins (27–540 tons, 1,000–20,000 bushels capacity), and nearly every small town has a grain elevator. A grain elevator is a storage facility consisting of a series of grain bins (270–5400 tons, 10,000–200,000 bushels capacity) served by vertical elevating equipment and, at some locations, by horizontal conveying equipment. Often, wheat first enters the marketing system at a country elevator, where grain is collected from the surrounding farms (Cramer and Heid 1983). Wheat then moves to a terminal elevator, a regional load-out facility or a river terminal where it is blended with other wheat and shipped to an export terminal or major domestic use point. Grain typically moves from the harvester to a farm bin or country elevator by truck, but some is trucked directly to a terminal elevator. Grain is moved from country to terminal elevators mainly by truck and railcar. Wheat may remain in storage at any of these locations from a few days to several years, although multi-year storage is increasingly rare in the United States because the government programs that encouraged long-term storage have been discontinued. The average storage time for wheat is probably in the range of 6–9 months. However, storage times depend upon the availability of local storage space and may be shorter when wheat needs to be moved to make room for the autumn crops of corn, grain sorghum (milo), soybeans, or others.

In contrast to perishable commodities and finished foods, wheat is usually stored during most of the year at near ambient temperatures, and shipped without protective packaging. Thus, insects are often able to survive throughout the grain marketing network. Within individual grain-handling facilities, insects survive in stored grain, the grain conveying equipment and empty bins. Grain conveying equipment on farms and in elevators consists of screw, drag, or belt conveyors, dump pits, and elevator legs. Typically, grain is unloaded from trucks into an elevator dump pit, which is a self-emptying, below-ground holding area that directs the grain into an elevator leg. After elevation, the grain may go directly to a distributor that can direct grain to any of the bins or enter a horizontal conveyor. The elevator legs, distributor and horizontal conveyors often have dead areas where grain and grain dust can accumulate. Areas retaining grain (retarders) are used to slow the descent of the grain when grain is dropped into a bin through a long spout. Insects in these accumulations of grain and fine material can later infest grain being moved through the conveying system.

Grain stores are either flat or upright. Upright stores are more than twice as tall as they are wide and are usually made of concrete, although some are made of metal sections bolted or welded together. Flat stores (2,700–54,000 tons, 100,000–2,000,000 bushel capacity), either cylindrical bins or warehouse-type, may be built of metal or concrete. In general, concrete stores are better able than metal structures to exclude insects, to insulate grain from changes in ambient temperature, and to retain fumigant. Bins have either flat bottoms or self-emptying hopper bottoms. In flat-bottom bins, a large amount of grain remains in the bin after emptying by gravity. This grain must be removed by manual labor, sweep augers, or some combination of manual and mechanical means. In hopper-bottom bins, a small amount of grain material usually remains in dead spaces after the grain is withdrawn. Grain residue and dust cling to the walls of bins, build up on ledges, and provide a moderately stable habitat for insect populations.

Insect-detection practices

Wheat is usually sampled to determine grain quality when received at elevators or moved from one bin to another bin. Sampling rates typically range from 1 part in 10,000 for a small farm truck to 1 part in 60,000 for an elevator bin and are designed to provide grain quality information for segregation, blending and marketing. Measures of grain quality important to the industry include color, test weight (bulk density), moisture and protein content, foreign or fine material, and damaged kernels. Sanitary condition including the presence of insects, insect-damaged kernels (IDK), and insect- or mold-related odors also are noted. Routine grain sampling practices focus on factors other than the presence of insects, and sampling rates are much too low to routinely detect sparse insect populations (Hagstrum and Flinn 1992). If the samples are passed over sieves or mechanical dockage testers, the insects are separated from the grain and can be observed in the fine material screenings (Demianyk et al. 1997). Occasionally, if insects are found and more information is desired, grain may be sampled in place or be moved to sample specifically for insects. This monitoring can confirm that insect populations have reached unacceptable levels, but often is insufficient to accurately estimate insect density per kilogram of grain. Accurate estimates of insect density are required to make sure that pest management decisions are correct.

In flat storages, many managers have workers probe the grain surface at fixed distance intervals to sample for insects. These samples are sieved to separate adult insects from the grain. In upright stores, where limited access to the bulk of the grain mass makes sampling more difficult, some managers regularly monitor grain temperatures, although most farm bins and many elevator bins are not equipped with temperature monitors. When unexplained temperature increases are detected, some grain is withdrawn and checked for insects or dampness. However grain heating due to insects occurs only after their populations have reached locally high densities of several hundred insects per kilogram of grain (Cofie-Agblor et al. 1995). Insects are detected outside elevator bins mostly by chance as floors and equipment are cleaned.

Because of the low grain sampling rate, insect-related quality factors are subjectively evaluated and inconsistently penalized (Reed et al. 1989, Barak and Harein l981a,b). Policies on discounts for insects or insect-related grade factors vary greatly from one elevator to another, and are applied less consistently than discounts for moisture, dockage, or test weight (Reed et al. 1989). Grain price discounts for the presence of live insects are more likely to be imposed when the test weight is low or when the dockage or fine material content is high.

Traditional insect pest control practices

Insect pest control practices for stored wheat vary between geographical regions and types of storage facilities. In southern parts of the United States wheat belt, insects are a greater problem than further north, and thus receive greater attention. Recommended insect-control practices include monitoring, sanitation, grain drying and cooling, and a variety of pesticides. The biological (Brower et al. 1995), physical (Fields and Muir 1995, Banks and Fields 1995) and chemical (Snelson 1987, White and Leesch 1995, Arthur 1996) methods of insect pest control available for stored grain have been reviewed. Grain protectants, which are applied directly to the grain as a dust formulation or a liquid spray as grain is loaded into a bin, kill insects by contact or ingestion. Fumigants, another type of pesticide, are commonly used in stored-grain as remedial treatments. The fumigants are gaseous poisons that kill insects as the gas enters their bodies through the spiracles. In North America, the phosphine fumigants are most commonly used in stored-grain. Some managers fumigate only when insects are detected. Others fumigate all of the grain in the storage facility before grain becomes too cold to fumigate in the autumn. Insect populations on farms (Hagstrum 1987) and at elevators (Storey et al. 1982) reach their highest densities and are most noticeable in the autumn. Traditionally, aeration also is done in the autumn (Cuperus et al. 1986).

Surveys have shown that on farms and at elevators, managers use a variety of pest management methods (Barak and Harein 1981b, Kenkel et al. 1993, Martin et al. 1997). Some managers use only remedial actions, whereas others use multi-tactic strategies including preventative methods. For example, on Kansas farms, about half of the farmers surveyed claimed to apply a grain protectant routinely (although biologically-active residues could be detected on only one-third of farms), whereas about a third of farmers did not plan to use a pesticide unless insects were found (Reed et al. 1990). At Kansas elevators, two-thirds of surveyed managers planned to fumigate only if an insect infestation was detected, whereas the remainder indicated that they fumigated on a pre-determined schedule (Worman et al. 1993). The predominant approach depends upon the geographical location, type of storage facility, and duration of storage.

On farms, bin sanitation and pesticide sprays are commonly used to disinfest bins before newly-harvested grain is stored. The use of grain protectants on wheat appears to be most common in the southern wheat production areas of the United States (Storey et al. 1984). Many farmers fumigate farm-stored wheat. Some aerate to cool the grain, and periodically monitor for grain quality problems, including insects, by sampling the grain near the surface. At elevators, where access to the grain is limited, fumigation is the most common pesticide treatment, although some grain, especially that likely to be stored for longer than 6 months, or in structures unsuitable for fumigation, is treated with residual grain protectants (Worman et al. 1993). Aeration to cool the grain and to moderate temperature gradients is also a common practice at elevators. Monitoring at elevators is typically done by sampling grain during movement or by detecting increases in grain temperature.

Effectiveness of traditional insect pest control practices

Information on the efficacy of insect pest management practices in the United States is available mainly for farm-stored wheat. Traditionally, farmers have depended more on grain protectants whereas elevator managers have fumigated.

On farms, empty bins are generally cleaned and treated with a pesticides to eliminate insect infestations before storing grain. Reed and Pedersen (1987) reported that empty bins which had been sprayed with a pesticide were as likely as unsprayed bins to have live insects present shortly before harvest. Also, treating an empty bin with a pesticide before harvest did not significantly reduce the level of insect infestation in wheat shortly after harvest. By September, grain stored in pesticide treated bins was significantly less likely to be heavily infested than grain stored in untreated bins (Reed et al. 1990), but the effect of applying pesticide to empty bins was not apparent in November, January or March. In South Dakota, Ingemansen et al. (1986) reported a reduction in the level of insect infestation in farm-stored grain after bins were cleaned with a vacuum cleaner shortly before harvest.

Farm-stored wheat treated with malathion grain protectant had significantly lower insect densities in November than did untreated grain (Reed et al. 1990). However, malathion breaks down within a month (Hagstrum and Flinn 1990) and the treated grain had a higher insect density than did untreated grain by January (Reed et al. 1990). In farm-stored wheat treated with chlorpyrifos-methyl grain protectant, insects were controlled for 5 months without grain cooling. After the fifth month, insect infestations increased, and grain deterioration was noted in the uncooled grain. However, grain treated with chlorpyrifos-methyl grain protectant at harvest and cooled in the autumn by aeration had few insects. The rate of pesticide degradation is slower in cool grain (Arthur et al. 1992). However, this grain protectant treatment was the most expensive of the insect-control strategies studied, and this pesticide generally is least effective against the lesser grain borer which is the most damaging pest of farm-stored wheat (Reed et al. 1990, 1993).

Storey et al. (1984) reported that grain samples from fumigated farm-stored wheat were as likely to be infested as those from unfumigated grain. Fumigations done too early or too late in the autumn appeared to have a low success rate (Reed and Worman 1993). This is consistent with simulation studies (Flinn and Hagstrum 1990, Hagstrum and Flinn 1990). Fumigation combined with grain cooling by aeration was the least expensive of the strategies studied by Reed et al. (1993). Kenkel et al. (1991) analyzed elevator manager's fumigation decisions and concluded that many managers applied fumigant based on habit or convention, rather than on evidence of need.

Many farm and elevator bins are equipped for aeration. Aeration equipment is more common in southern than northern wheat production areas of the United States (Kenkel et al. 1993). Kenkel et al. (1994b) reported that at least 75% of farm bins and 93% of steel bins at elevators in Oklahoma were equipped for aeration. In Kansas, 61% of farm bins had aeration equipment (Reed and Pedersen 1987). In a South Dakota study, less than 5% had aeration equipment (Ingemansen et al. 1986), and in a Minnesota study, less than 25% of wheat bins had aeration equipment (Barak and Harein 1981b). Managers' aeration practices appear to be highly variable. Reed and Pedersen (1987) reported that only 17% of farm-stored wheat bins were aerated by November, even though more than half had aeration equipment.

At elevators, most steel (81%) and concrete (51%) bins in wheat production areas are equipped for aeration (Kenkel et al. 1993). Managers' responses to questions about aeration management indicate that their practices are variable. Although about half of the respondents indicated that they aerated commercial stores in October, November, and December, 15–32% indicated that they aerated during other months, including the summer. When managers were asked about the number of aeration cycles and target grain temperature, their answers were highly variable. In Kansas, about half reported beginning aeration immediately after harvest (Reed and Worman 1993), whereas the remainder waited for cool autumn temperatures. About half aerated continuously during the aeration cycle, whereas the remainder aerated at night or intermittently.

The effectiveness of aeration as an insect-control technique appears to depend on how well it is managed. Well-managed aeration has been shown to provide economical control of insects in farm-stored wheat in southern Kansas (Reed and Harner 1998). Further north, complete control with aeration has been demonstrated (Halderson 1985). Flinn et al. (1997) have shown using simulation studies that the use of automatic aeration controllers might be expected to effectively suppressed insect population growth in Oklahoma, Kansas and South Dakota if aeration was started soon after newly-harvested grain was stored. Although similar data are not available for elevator storage, managers' comments indicate that many believe that they can routinely control insects by cooling grain with aeration and good sanitation practices.

Cost of insect pest control

The cost of insect pest control includes the cost of monitoring for insects and the cost of insect control measures such as grain protectants, aeration and fumigation. The costs of sampling grain for insect was estimated to be $0.07/ton ($0.002/bushel) (Hagstrum and Flinn 1995) and the time required to count the number of insects caught in probe traps was estimated to be 1.3 min plus 0.038 min for each insect caught (Subramanyam et al. 1989). The cost of applying residual pesticides to stored wheat in 1990 and 1991 was estimated at 18.7–65.6¢/ton (0.5–1 .9¢/bushel) depending on the pesticide used (Reed et al. 1993). Kenkel et al. (1993) similarly estimated of the cost of grain protectants as 14.1 or 81.4¢/ton (0.38¢ or 2.2¢/bushel), depending on the pesticide used. These authors also estimated the cost of empty bin treatments at 0.033–25.9¢/ton (0.0009–0.01¢/bushel capacity) depending on the type of storage structure and the pesticide used. Overhead costs include the cost of the application equipment.

The costs of traditional aeration, once in the autumn and again in the winter, was estimated at approximately 18.7–25.9¢/ton (0.5–0.7¢/bushel) for electricity (Noyes et al. 1991). Overhead costs include the initial installation of roof vents, floor ducts and fans.

The cost of fumigation includes the costs of the fumigant, materials used to seal the bins, air monitoring tubes and other materials. The labor costs for sealing, applying fumigant, air monitoring, unsealing and de-placarding are also major costs of fumigation. Overhead costs such as those related to the ownership of respiratory protection and other personal protection equipment also should be considered. Kenkel et al. (1993) estimated that the cost for fumigation was 58.09¢/ton (1.57¢/bushel) in steel and 86.95¢/ton (2.35¢/bushel) in concrete storage structures. This represents 8% and 13% of the elevator's grain handling and storage profit margin.

Costs of insect presence or damage

Domestic wheat market and export transactions are based on both United States grade and supplemental quality specifications. The presence of live insects or IDK may reduce wheat value by lowering the grade or by causing the load to be discounted or rejected. According to the United States grain standards, wheat containing 2 or more live insects injurious to stored grain per kilogram grain sample receives the special designation of 'infested' which is noted on the grade certificate. The market penalties for insect presence are set by the individual grain buyer. Historically, market penalties for delivering insect-infested wheat have been relatively low. Reed et al. (1989) found that the discount for delivering wheat with 1 or more live insects per kilogram grain sample to Kansas elevators ranged from $0.04/ton (0.1¢/bushel) to $22.05/ton (60.0¢/bushel). When the effect of other grade factors such as bulk density was removed, the mean discounts for the presence of 0.1–1, 1.1–5, or >5 live insects per kilogram grain sample were $0.74/ton (2.0¢/bushel), $0.77/ton (2.1¢/bushel), and $1.51/ton (4.1¢/bushel), respectively. The authors concluded that discounts for live insects were more variable and inconsistent than discounts for other grade factors. Anderson et al. (1990) concluded from the same data that the penalties did not provide enough incentive for risk-adverse managers to apply expensive treatments to control insects. Kenkel et al. (1991) did a similar risk analysis for elevators.

In recent years, there has been a general trend toward a decreased tolerance of live insects. Domestic flour millers report a zero tolerance for live insects (Kenkel et al. 1993). The occurrence of a single insect-infested grain sample may result in the rejection of an entire truck, train or barge load of grain. If a load is rejected, the grain must be either transported to another market outlet with less stringent standards or to a location where it can be fumigated. The cost of a rejected load depends on the relative price at other market outlets and the transportation and fumigation costs involved.

The cost of a rejected load can be as much as 10–20% of its value and is often the major concern of most elevator managers.

The presence of IDK also may reduce the value of wheat if the grain fails to meet the contract specifications. High IDK counts may reduce the numerical grade or, in extreme cases, result in a ‘sample grade’ designation, which requires that the wheat not be used for food products. Domestic flour mill contracts specify an upper rejection limit of 7 IDK per 100 g grain sample (Kenkel et al. 1993). At a terminal elevator, price discounts of 37–74¢/ton (1–2¢/bushel) for each percent total grain damage above a threshold of 5–7% are typical (Attaway 1998). Under the United States wheat standards, a sample containing more than 2% total damaged kernels, which represents 20–30 kernels per 100 g grain sample, does not qualify for the United States #1 grade designation, and higher percentages cause further grade reductions.

Marketing system trends affecting insect control

The grain storage system in the United States, and insect control are affected by macro-economics, business decisions, and political factors. During the last decade, several changes in the wheat marketing system have influenced insect control in stored wheat. Mergers and consolidations have reduced the number and increased the size of companies and cooperatives. This may promote more centralized and uniform insect pest management programs, and more rapid adoption of new methods.

Storage facilities

Most of the grain elevators currently being used in the United States were built in the 1950s and 1960s (Reed 1992). Because the cost of constructing upright concrete bins has increased more rapidly in recent decades than that of metal storage bins, much of new elevator space is metal bins. These bins are usually larger and are more likely to have aeration equipment than concrete bins, but they have less thermal insulating capacity, are more accessible to insects, and are more difficult to seal for fumigation. In metal bins, phosphine tablets are often probed into the grain, whereas in concrete bins, phosphine tablets are usually added using an automatic dispenser as the grain is turned from one bin to another. The greater difficulty in fumigating steel storage structures, and the increasingly more stringent safety requirements have resulted in increasingly more of the fumigation at elevators being done at increased cost by commercial pest control operators.

Government policies

In the United States, changes in government policies on grain production and storage, and the deregulation of the transportation industries have influenced stored-grain insect pest management. Cropping patterns are changing in response to changes in the United States Department of Agriculture farm program. This has sometimes resulted in grain being stored in facilities designed for other commodities, and managed by persons without wheat-storage experience. The elimination of subsidies as incentives for long-term storage has reduced the amount of grain carried over from one crop year to the next. At the same time, the cost to the grain industry of compliance with safety and pesticide regulations has increased. Over time, this may reduce the amount of regulated pesticide used in commercial elevators. Changes in the rate structure for railroad transportation have resulted in more grain being moved by truck than ten years ago and grain is now less likely to be officially inspected. The rate changes also have made it more likely that wheat used domestically will be stored at the first handler level (country elevator) rather than at terminal elevators. Grain moving to export is received at traditional terminal elevators or new regional high-speed loading facilities which have the capability to efficiently load 25–100-car unit trains. With inexperienced managers and fewer official inspections, the quality of insect pest management is examined less. Shorter storage periods have made insect pest management easier while the regulations that have increased the cost of pesticide use have made insect pest management more challenging.

Consumer interests

Increased consumer concerns about food safety and wholesomeness were to some extent responsible for the 1988 changes in the United States wheat standards. Those changes reduced the tolerance for live insects in wheat receiving a grade designation, and allowed for the separate reporting of IDK. Flour mills apparently reduced their tolerances for insect infestation and kernel damage at about the same time.

Foreign and domestic consumers also have become increasingly vocal about pesticide residue concerns.

Many foreign customers have privatized grain importation during the 1990s and have become more discerning about grain quality (Stephens 1997). In 1994, the Japanese wheat purchasing agency implemented a program of bonuses and discounts to reduce the amount of dockage that is acceptable in wheat imported from the United States (Grain Elevator and Processing Society, 1995). Physical and sanitary quality issues are now more important than previously in wheat contracts.

Integrated pest management

The management of stored-grain insect pests can perhaps benefit from the experience of entomologists working with insect pests in other situations. The concept of integrated pest management (IPM) was developed as a method of making pest management decisions by field crop entomologists (Stern et al. 1959) and was later adopted as a suitable operational plan for solving many other types of insect pest problems. IPM is ecologically-based, and integrates chemical and nonchemical pest management methods to minimize the problems associated with chemical control such as resistance of insect pests to pesticides, pesticide residues, and worker and consumer health risks. It also maximizes cost-effectiveness by minimizing the costs of pesticide use and optimizing control by natural enemies.

The use of IPM for ornamental plants and cockroaches in urban environments may be particularly relevant to stored-product insect pests because this application emphasized aesthetic damage instead of yield reduction (Raupp et al. 1987). Often, the presence of stored-grain insect pests in a commodity can cause economic losses such as penalties for delivering insect-infested grain, fumigation costs or added shipping costs before there is measurable damage to the commodity.

Although many definitions of IPM have been proposed (Cate and Hinkle 1994, Kogan 1998), the operational plan for IPM has two key elements, monitoring-based decision making and the use of multiple pest control tactics. Monitoring-based decision-making minimizes the cost of pest management and reduces the risk of economically damaging insect infestations. Multiple tactics are used mainly to slow the development of insect resistance to pest control methods such as pesticides, and to make insect pest management more effective and sustainable. Both of these elements were discussed in the paper by Stern et al. (1959) that first proposed the operational plan for IPM.

Stern et al. (1959) were responding to problems inherent in the overuse of insecticides, namely, resistance of insect pests to pesticides and resurgence of pest populations. Many species of insect pests had become resistance to insecticides. Insecticide applications were killing natural enemies leading to outbreaks rather than suppression of pest populations. Their solution was to reduce the frequency of insecticide applications, to use insecticides that were less toxic to natural enemies and to use ecologically-based pest management methods such as natural enemies and crop rotation instead of insecticides whenever possible. The term ‘integrated’ was used to emphasize the importance of finding compatible combinations of chemical and biological control.

Stern et al. (1959) proposed that insecticides be used only when the insect monitoring program indicated that insect pest populations were likely to reach an economically damaging level which they called the economic injury level (EIL). This concept recognized that some densities of insect pests can be tolerated and that control is economical only when the cost of the damage caused by the insect pests exceeds the cost of insect control. They also proposed the use of an economic threshold (ET) which is the insect density at which control must be applied to prevent insect population densities from reaching the EIL. The ET allows for a delay between the application of insect control measures and the suppression of insect populations, and is generally calculated as a percentage of the EIL. Stone and Pedigo (1972) proposed using an equation for determining whether the cost of damage had exceeded the cost of control. Onstad (1987) elaborated on the usefulness of such calculations for choosing the most economical insect pest management method and for scheduling its use.

Stored-grain IPM

Some of the approaches recommended for stored-grain insect pest management are similar to those of Stern et al. (1959). IPM for stored grain has been discussed by Evans (1987), Hagstrum and Flinn (1992), Cuperus et al. (1993), Kenkel et al. (1994a) and Hagstrum and Flinn (1995). Ecologically-based methods such as cleaning bins before storing grain and aeration to slow insect population growth by cooling grain are important components of stored-grain insect pest management. Regular insect monitoring is recommended for stored-wheat to determine whether fumigation is needed, although the levels of grain sampling often are not sufficient to accurately estimate whether insect densities have reached an ET and precise EIL have not been developed. In contrast, EIL have been reported for more than 70 insect species on 43 major crops during production (Peterson 1996). As with these crops, the overuse of pesticides is becoming a problem with stored-grain because insects have developed resistance to a range of insecticides and fumigants (Subramanyam and Hagstrum 1995b). Unlike field crops, the role of natural enemies generally has not been considered to be significant in stored grain. Only recently has research shown that parasites can reduce insect pest populations to acceptable levels in stored-wheat (Hagstrum 1987, Flinn et al. 1996). Naturally-occurring parasite species are known to attack all of the major pests of stored-wheat (Hagstrum and Flinn 1992). The conservation of naturally occurring parasites and predators needs to be considered in designing and implementing pest management programs for stored-wheat.

A number of differences between stored-grain and field crops need to be considered in developing a stored-grain IPM program. Stored-grain cannot compensate for insect damage as growing plants can, so grain quality only decreases during storage. Thus, stored-grain may tolerate fewer insects than field crops and have a lower EIL. The major insect pest risks for stored-grain are the cost of discounts, rejected loads, and the associated loss of reputation. These types of risks rather than a risk of reduced yield of field crops make it more difficult to reduce pesticide use for stored-wheat. Another distinctive characteristic of stored-grain insect pest management is that pesticides can only be economically applied during a few brief time periods. Residual insecticides can be applied economically to the grain only when newly-harvested, insect-free wheat is first placed in the bin. In contrast to field crops, in which pesticide applications are often delayed in response to scouting reports, the fumigation schedule for stored-grain is often controlled by grain temperature because fumigants work poorly below 5°C or by the time that the grain is moved to another bin.

Although storing wheat from hundreds of acres in a single bin eliminates travel between fields, grain stored in such large masses is less accessible for insect monitoring. This inaccessibility has favored preventative methods and fumigation when grain was turned for managing stored-grain insects. Environmental and safety issues also are different from those of production agriculture. A major issue for field crops is ground water pollution with insecticides washed off of plants by rain. For stored grain, a similar issue may be the release of fumigants into the air. Regulations have been enacted for release rates of phosphine from tobacco warehouses in North Carolina and Virginia (Keever and Hamm 1996).

Another major difference between field crops and stored-grain is the availability of private consultants and scouting services for field crops (Lambur et al. 1989) while the pesticide industry is still the primary source of information for grain producers and elevator managers (Cuperus et al. 1990). The pesticide industry may tend to promote only pesticide use because their profits increase as the volume of pesticide sales increases. Because of the complexity of IPM, private consultants are likely to be quite important in moving from traditional pest control to IPM (Glass 1975, Flint and van den Bosch 1981, Frisbie and McWhorter 1986, Vandeman et al. 1994, Dent 1995, National Research Council 1996). In production agriculture, consultants charge a per acre fee for monitoring insect infestations, interpreting the results and providing pest control advice (Hall 1977). Consultants have an economic incentive to minimize pesticide use, because the greater the savings in the pesticide application cost resulting from careful monitoring, the larger the fee per acre that consultants can charge the grower. Although consultants can facilitate the use of new, more technical, ecologically-based IPM programs, they may need to use the simplest, least expensive methods to remain competitive (Hutchins 1995).

Cost–benefit analysis

Key factors in any pest management decision are the costs and benefits. Cost–benefit analysis refers to the formal process of comparing the costs with the benefits of a pest management decision (Gittinger 1982). A cost is anything that reduces the chances of attaining a decision-maker's objective and a benefit is anything that contributes to attaining that objective. Studies on the economic evaluation of IPM programs have been reviewed by Norton and Mullen (1994). For grain producers and elevator managers, maximizing net income is a major objective. For this reason, most cost–benefit analyses concentrate on the impact of a proposed stored-grain insect pest management decision on revenues and costs. Another objective of stored-grain insect pest management is minimizing the risk of economically damaging infestations. This objective also can be considered within the context of the cost–benefit analysis but is more subjective.

Area-wide IPM

Area-wide IPM programs have been developed for orchards, public health pests and field crops because insect dispersal from infested to uninfested areas is extensive. Examples are the citrus protective districts in California (Graebner et al. 1984), mosquito control districts, and the screwworm and boll weevil eradication programs in the United States (Myers et al. 1998). Area-wide IPM can reduce the cost of pest management by gradually suppressing insect populations in large areas, and thus reducing the chances of reinfestation and the need for additional pest control. Bellows (1987) developed a simulation model for optimizing the distribution of pest management effort over a region.

Area-wide IPM programs are important for stored grain because insects are moved along and multiply as grain passes through the grain marketing system from farm to country elevator to terminal elevator to flour mill or export (Hagstrum and Flinn 1992). Pest management is likely to be much more effective if IPM is used uniformly throughout the wheat marketing system. Area-wide IPM for the 80 country and 4 terminal storages of a central bulk handling system in Australia reduced the number of control failures and the number of storages infested from 60% to 16% (Bridgeman and Collins 1994, Collins and Bridgeman 1997). The cost of the pesticides used was reduced from $1.50/ton to $0.60/ton and the number of storages with insecticide residue-free grain increased from 30% to 90%.

Moving from traditional pest control to IPM

Adapting the IPM concepts discussed in the previous section to the United States wheat storage system described in the first section will require several changes in pest management practices. Traditional stored-grain insect pest control is multi-tactic, i.e. sanitation, aeration and pesticides, but insect monitoring data are generally inadequate for pest management decision making and nonchemical methods are often not used to their full potential. Inspections are designed to provide grain quality information for segregation, blending, and marketing, and to identify areas in a facility where major outbreaks are likely. In the current system, the risks of economic loss due to discounts or rejected loads resulting from insect presence or damage are sometimes managed using multiple tactics, but the selection of tactics and the timing of their use are not guided by adequate information on insect pest population densities. Fumigation is generally done in response to inaccurate information on insect population densities, or done just prior to shipping to reduce the risk of a detectable live insect infestation. The research needed to develop ET has not been done and cost–benefit analysis is not used to make pest management decisions.

To move from traditional insect pest control to an IPM program for stored-grain insects that is comparable to those successfully used in field crops, the following changes will be required. First, greater emphasis will need to be placed on sampling grain to estimate whether insect density has reached an ET. An IPM program in which pesticides are used only when insect densities exceed an ET and other methods are not available is likely to be less risky and more economical. The risk of economic losses will be reduced by controlling insect populations before they spread to other grain, and by minimizing the chances of unforseen insect problems. The cost of insect pest management will be reduced by fumigating less grain or by using less expensive methods such as detecting insect infestations early and selling grain before insect pests reach unacceptable levels. Second, prophylactic components such as sanitation and aeration will receive greater emphasis and their effectiveness will be enhanced. Early aeration using fan controllers, and monitoring-directed sanitation will make insect pest management more effective and less expensive. Selective pesticide applications will be more effective with better information about the distribution of insect populations. With more selective use of pesticides, naturally-occurring or released natural enemies will be more effective in suppressing insect pest populations. Parasites were found to be more effective at 25°C than at 32°C and are therefore likely to be more effective in combination with grain cooling by aeration (Flinn 1998).

IPM can provide for grain storage the same benefits that it has provided for crop production. More judicious and selective application of pesticides will increase the useful life of pesticides by decreasing consumer health concerns, thus reducing anti-pesticide sentiment, and by delaying the onset of insect resistance to pesticides. It is also likely to reduce the number of pesticide applications, helping to conserve natural enemies and reducing worker exposure. IPM also will most certainly decrease the risk of economic loss due to insect-infested shipments. Moving from traditional stored-grain insect pest control to IPM will shift risk management from routine pesticide applications to monitoring-based decision making.

The major costs of IPM adoption are likely to be those for collecting grain samples and checking them for insects, and the costs of educating stored-grain managers and their employees in ecologically-based insect pest management. At the same time, the costs of turning and blending grain, and certain pesticide treatments may be reduced by better management. We anticipate that a major benefit would be a reduction in fumigation costs as monitoring-based applications replace routine applications. Another potential benefit would be a reduction in insect-related market discounts and rejected loads as increased monitoring reduces the likelihood of an undetected insect infestation. At flour mills, a parallel benefit might be decreased likelihood of excessive fragment counts and pesticide residues in flour. IPM programs also may open new market opportunities or maintain access to existing market outlets which are increasingly more concerned about grain quality, insect presence and pesticide residue levels.

Improved pest management methods

The results of recent research can make IPM, with its reliance on monitoring rather than 'insurance' pesticide applications to manage risk, more attractive to elevator managers. Research on insect monitoring, predictive models, biological control, cooling by aeration, and fumigation techniques is likely to improve pest management.

Insect monitoring

The steps in developing a sampling program for stored-grain insects have been reviewed (Hagstrum 1994, Hagstrum et al. 1995, Subramanyam and Hagstrum 1995a). Most of the sampling programs that have been developed for stored-grain insects are for farm storage, but some work has been done at elevators (Smith and Loschiavo 1978, Smith 1985, White 1985, 1988, Mahmood et al. 1996). Recent research directed toward improving insect monitoring includes the development of equipment for sieving large grain samples to separate insects, better methods of collecting, analyzing and interpreting sampling data, and automation of insect monitoring. Larger samples can provide earlier detection of insect infestations because insect infestations can be detected at lower densities. Better methods of interpreting sampling data and automation can improve insect pest management decisions by providing more accurate information about insect infestation levels and reducing the cost of sampling.

More wide-spread use of automatic pneumatic truck samplers and diverter samplers at elevators will make it easier to collect large grain samples for insect monitoring. Three devices for separating insects from large grain samples have been tested. White (1983) developed an inclined sieve for processing 25-kg wheat samples and found that 95% of lesser grain borers, rice weevils and the red flour beetles, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) were recovered with 2, 3 or 4 passes over the sieve, respectively. Wilkin et al. (1994) improved upon the inclined sieve by developing a motorized shaker that can remove nearly 100% of the granary weevil, *Sitophilus granarius* (L.) (Coleoptera: Curculionidae), and the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae), from a 10-kg sample in 1.8 min. Demianyk et al. (1997) found that a mechanical dockage tester removed 84–91% of adult rusty grain beetles, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae), and 57–81% of larvae from kilogram grain samples.

Improvements in the collection, analysis and interpretation of sampling data include the development of sequential sampling plans, generic sampling statistics and new methods of collecting and interpreting trap catch data. Sequential sampling plans can minimize the number of samples needed to accurately estimate insect density because at high insect densities, fewer grain samples are needed to achieve the same level of accuracy than at low insect densities. Subramanyam et al. (1997) developed a fixed-precision and a binomial sequential sampling plan for adult rusty grain beetles.

Predictions of variance as a function of the mean insect density or mean trap catch have been widely used in planning sampling programs and evaluating their performance. Before beginning a study, preliminary data are collected to fit a variance-mean regression equation. The amount of data needed to accurately fit the equation makes this expensive. Hagstrum et al. (1997) have developed a generic nonlinear variance-mean regression equation for stored-grain insects that can reduce the cost of developing a sampling program by eliminating the need to collect preliminary data.

Traps are often easier to use than are other methods of estimating insect density. However, estimates of insect density based upon the number of insects caught using probe traps differed from those based upon the number of insects found in grain samples, and the economic thresholds for traps were different from those for grain samples (Hagstrum et al. 1998, Vela-Coiffier et al. 1997). Also, seasonal changes in temperature and other factors can influence trap catch more than the density estimates made using other methods. Thus, trap catch was found to be inconsistent in estimating insect population density during the storage period (Hagstrum et al. 1998) Equations were developed in this paper for converting trap catch to insect density per volume of grain by adjusting for the effect of temperature on trap catch. These methods will increase the usefulness of traps as insect monitoring tools. Equipment also has been developed for electronically monitoring probe trap catches (Shuman et al. 1996).

Automation allows more intensive and frequent sampling than is practical with manual grain sampling methods, and provides more accurate and up-to-date information on insect infestation levels with which to make insect pest management decisions. The efficacy of using acoustical sensors on cables to monitor insect populations in wheat stored in farm bins has been demonstrated (Hagstrum et al. 1996). Acoustical sensors detected insects in each of 9 bins in which insects were found in grain samples and often detected insect infestations 2–4 weeks earlier than intensive conventional grain sampling. The number of times that insect sounds were detected was correlated with insect density in grain samples over a density range of 0–17 insects per kg of grain. The study indicated that a smaller version of the automated system with sensors located only in the top center of a farm bin could provide a cost-effective, early-warning system for the most damaging insect pest, the lesser grain borer. Automation will be particularly worthwhile at large grain storage facilities where it is difficult to check all of the grain thoroughly and frequently enough to detect infestations before the insect populations have reached unacceptable levels. Acoustical sensors could be added to the cables that are currently used to monitor grain temperature. An automated system would allow the level of insect infestation in each bin to be checked from a computer in the main office. This information could be used to determine which grain to sell first. Networking of computers would allow individual lots of grain to be followed as they are moved through the marketing system.

Predictive models

A computer model has been developed to forecast insect population growth, when pest control will be needed and the efficacy of pest management programs (Hagstrum and Throne 1989, Flinn and Hagstrum 1990, Hagstrum and Flinn 1990, Flinn et al. 1992, 1997). Models are useful because grain temperature and moisture, which are the main factors influencing insect population growth rates, are more easily measured than insect densities. Therefore, insect population growth rates can be predicted from grain moisture and temperature. The development of these and other models for predicting insect population growth has been reviewed by Throne (1994).

A model predicting the population growth rates of the 5 species of stored-wheat insect pests most commonly found in the United States has been improved by adding winter survival of lesser grain borers (Hagstrum and Flinn 1994), by validating the predictions for lesser grain borer over a broader range of temperatures (Hagstrum 1996), by providing methods of predicting seasonal changes in grain temperature (Flinn et al. 1992) and the effectiveness of low oxygen atmospheres for insect control (Flinn and Hagstrum 1997), by including methods of simulating different aeration strategies (Flinn et al. 1997), and by adding parasites to simulate the effectiveness of biological control for rusty grain beetles (Flinn and Hagstrum 1995). Stored Grain Advisor, an expert system for stored grain management (Flinn and Hagstrum 1994), provides a way for farmers and elevator managers to more easily use these predictive models to make insect pest management decisions. In field trials, this expert system was shown to make correct recommendations 80% of the time without using grain sampling information (Flinn and Hagstrum 1994). Using insect density estimates from grain sampling should increase the reliability of these recommendations. Expert systems for stored-wheat management also have been developed in Australia (Longstaff and Cornish 1994), Canada (Mann et al. 1997) and the United Kingdom (Wilkin and Mumford 1994).

By simulating the cost and effectiveness of several insect pest management programs, the most economical pest management program that provides the best long-term pest management can be selected. The model predictions also can be used to reduce the cost of insect sampling programs. By predicting future insect population densities, grain sampling to estimate insect density can be done only when needed rather than on a calendar schedule and thus the cost of sampling can be reduced. A model predicting the seasonal changes in insect populations in the wheat-marketing system may be useful in developing an area-wide IPM program for elevator networks (Hagstrum and Heid 1988).

Grain cooling by aeration

Recent advances in the use of aeration for insect control have improved our understanding of the impact that grain temperature manipulation can have on feral insect populations, and thus provided more precise recommendations for operating aeration fans. Sophisticated programmable fan controllers, which have been available for many years, appear to be used principally to cool or dry grain without overdrying. The use of inexpensive, single-thermostat aeration fan controllers to provide maximum cooling with only ambient air while minimizing fan-hours has recently been investigated in field trials (Reed and Harner 1998). These studies indicated that insect populations can be controlled effectively for farm-stored wheat in Kansas without routine pesticide use if the aeration system delivers at least 0.09 m^3/min/ton (0.1 CFM/bushel).

In the Reed and Harner (1998) study comparing an early grain cooling strategy using automatic aeration controllers with a strategy that delayed cooling until autumn, the early cooling strategy was less expensive. For a 190-ton (7,000-bushel) lot of farm-stored wheat, the electrical cost for early cooling was estimated to be \$0.37/ton (0.3¢/bushel) more than that for delayed cooling. However, the early cooling strategy increased grain moisture content slightly, whereas the delayed cooling strategy decreased grain moisture content slightly. Because the difference in market value due to this difference in wheat moisture content more than offset the higher electrical costs of early cooling, the payback period for a \$600 aeration fan controller and the additional electricity for early cooling was 1 year.

Because insects were better controlled by the early-aeration strategy, the mean discount if the wheat had been marketed in September would have been only \$0.33/ton (0.9¢/bushel) for the early-cooling strategy compared with \$0.92/ton (2.5¢/bushel) for the delayed-cooling strategy. If managers had fumigated grain containing more than 1 insect per kilogram to avoid discounts, 1 of 5 lots with early-cooling would have needed fumigation compared to 4 of 5 lots with delayed-cooling. Optimum strategies for aeration control are now being developed for other wheat production areas in the United States.

Fan controllers to cool grain as quickly as possible are not new, but previously have been used more to control grain moisture rather than insects. It is possible that grain managers may tend to use pesticides rather than aeration to control insects because they are easier to use and appear to be less expensive than aeration which requires a large initial investment. However, pesticides must be purchased every time grain is stored whereas aeration equipment is long-lasting and operating costs are small. The greater knowledge and skill required to manage insects with aeration also favors the use of pesticides.

Many upright concrete grain silos in wheat production areas have no aeration or are equipped with systems that deliver 0.046 m^3/min/ton (0.05 CFM/bushel) or less. Research is underway to determine if cross-flow aeration systems (Converse 1967), which use small fans to deliver the airflow required for the early-cooling strategy, can be inexpensive enough to be used as the primary method of insect control in upright silos.

Grain cooling with large, portable air conditioners called grain chillers is another technology that has been used sparingly for decades in the United States, but has recently been reinvestigated (Maier 1994) because of the changing economic, marketing, and political environment. Maier et al. (1997) reported that chilling wheat in the summer from 25–27°C to 15–17°C cost \$0.41/ton with run times of 180–240 h. A separate analysis showed annual operating costs of \$1.49/ton for chilling compared with \$2.98/ton for fumigation followed by aeration. Grain chilling is common in some areas of the world, but in North America is used mostly for higher-value grain products (i.e. specialty rice, organic grain), and grains and seeds that have special humidity requirements (i.e. popcorn, specialty beans).

Biological control

Parasites attack most of the major stored-wheat insect pests (Hagstrum and Flinn 1992), and many of these parasite species are frequently found in stored wheat. Using IPM to manage stored wheat will conserve these naturally-occurring parasites by reducing the use of pesticides that kill the parasites. In stored wheat, naturally-occurring parasites were found to reduce rusty grain beetle populations by 50% (Hagstrum 1987), and released parasites were found to reduce lesser grain borer populations by 98% (Flinn et al. 1996). Parasites were found to be more effective at 25°C than at 32°C and are therefore likely to be more effective in combination with grain cooling by aeration (Flinn 1998). Parasites and predators can be purchased for release from a number of different companies (Hunter 1997). The cost of biological control using parasites and predators was estimated to be \$1.50/ton (\$0.04/bushel) (Flinn et al. 1996). The key to cost–effective use of innoculative or innundative biological control is releasing the correct species and numbers of natural enemies at the right time. Computer models will be helpful in designing biological control programs (Flinn and Hagstrum 1995).

Fumigation

Better management of pesticide resistance is often an expected benefit of IPM programs. The alternating use of various chemicals, as is recommended for pesticide resistance management (Subramanyam and Hagstrum 1995b), is not a viable option for grain fumigation because phosphine is at present the only economically-viable product for stored-wheat insect pest management at most grain elevators in the United States. Therefore, pesticide resistance will need to be managed by more effective use of nonchemical methods or by reducing the number of applications. Research is currently underway at elevators to develop more precise insect detection and pest management decision-making tools that will recommend fumigation only when necessary.

Research also is underway to increase the effectiveness and safety of the phosphine fumigants, and reduce the amount of phosphine required for adequate control. Inert gases can be used alone or in combination with phosphine to improve its effectiveness. Some countries have very active research and development programs on the use of modified atmospheres for stored-grain insect control, but commercial grain managers in the United States have shown little interest. Inert gas and fumigant combinations have found a niche in certain speciality grain products (Industrial Fumigant Company 1996). Combination fumigations have been done commercially, mostly in processing facilities, although new fumigant products have recently been developed for grain stores (Winks 1993). Some of the combination fumigation techniques require manipulation of the temperature as well as the atmospheric gas concentrations (Fumigation Service and Supply, Inc. 1996).

Re-circulation fumigation wherein fumigant is forced through the grain, is a patented technique used mostly in hard-to-fumigate structures such as ship holds and flat steel bins (Noyes and Kenkel 1994). Noyes et al. (1995) examined the costs and benefits of installing re-circulation fumigation systems in commercial elevators. The major cost was the original construction and installation cost of 29.6–48.1¢/ton (0.8–1.3¢/bushel). The benefits included savings in labor of 1.85¢/ton (0.05¢/bushel) and fumigant of 5.55¢/ton (0.15¢/bushel). The cost–benefit analysis indicated that the re-circulation systems had a payback period of approximately 4 years. Currently, re-circulation fumigation is being adapted to upright concrete storage.

Research needs

Recent changes in grain marketing practices may affect insect pest management needs. Research is needed to determine whether current pest management programs are the most cost-effective in reducing the risk of loss due to insect infestation. The efficacy of aeration, biological control and fumigation in maintaining insect pest populations below economically-damaging levels has not been adequately evaluated under field conditions. Research is needed to determine the effect of the recommended pesticide application practices on populations of natural enemies. Also, research is needed on conserving and optimizing the effectiveness of naturally-occurring populations of parasites. Full utilization of IPM in wheat storage in the United States is likely to require research to develop more precise economic-injury levels and more cost–effective sampling programs for insect monitoring.

References

Anderson, K., Schurle, B., Reed, C. and Pedersen, J. (1990) An economic analysis of producers' decisions regarding insect control in stored grain. *North Central J. Agric. Econ.* **12**, 23–29.

Arthur, F.H. (1996) Grain protectants: Current status and prospects for the future. *J. Stored Prod. Res.* **32**, 293–302.

Arthur, F.H., Throne, J.E. and Simonaitis, R.A. (1992) Degredation and biological efficacy of Chlorpyrifos-Methyl on wheat stored at five temperatures and three moisture contents. *J. Econ. Entomol.* **85**, 1994–2002.

Attaway, R.D. (1998) Wheat grading accuracy and potential profit from segregation and blending. Masters Thesis, Department of Agricultrual Economics, Oklahoma State University, Stillwater.

Banks, J. and Fields, P. (1995) Physical methods for insect control in stored-grain ecosystem. In D.S. Jayas, N.D.G. White and W.E. Muir (eds) *Stored-Grain Ecosystems* pp. 353–409. New York: Marcel Dekker, Inc.

Barak, A.V. and Harein, P.K. (1981a) Unpredictable penalties at time of sale applied to insect-infested farm-stored grain in Minnesota. *Bull. Entomol. Soc. Amer*. **27**, 166–9.

Barak, A.V. and Harein, P.K. (1981b) Losses associated with insect infestation of farm stored shelled corn and wheat in Minnesota. Minnesota Agricultural Experiment Station Misc. Pub. 12-1981, St. Paul.

Bekon, A.K. and Fleurat-Lessard, F. (1992) Assessment of dry matter loss and frass production in cereal grain due to successive attack by *Sitophilus oryzae* (L.) and *Tribolium castaenum* (Herbst). *Insect Sci. Applic*. **13**, 129–136.

Bellows Jr., T.S. (1987) Regional management strategies in stochastic systems. *Bull. Entomol. Soc. Amer.* **33**, 151–154.

Bridgeman, B.W. and Collins, P.J. (1994) Integrated pest management in the GRAINCO, Queensland Australia, storage system. *Proc. Sixth International Working Conference on Stored-Product Protection* pp. 910–4. Wallingford, U.K.: CAB International.

Brower, J.H, Smith, L., Vail, P.V. and Flinn, P.W. (1995) Biological control. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products* pp. 223–86. New York: Marcel Dekker, Inc.

Cate, J.R. and Hinkle, M.K. (1994) *Integrated pest management: The path of a paradigm*. Washington, D.C.: National Audubon Society.

Cofie-Agblor, R., Muir, W.E. and Sinha, R.N. (1995) Comparative heat of respiration of five grain beetles in stored wheat. *Postharvest Biol. Technol.* **5**, 167–75.

Collins, P.J. and Bridgeman, B.W. (1997) Strategic planning for effective integrated pest management in private industry: A case study. In J.L. Steele and O.K. Chung (eds) *Proc. Intern. Wheat Quality Conference*, pp. 413–21. Manhattan, Kansas: Grain Industry Alliance.

Converse, H.H. (1967) A two-fan crossflow ventilation system for upright grain storages. *ARS 52-20*, p. 18. Washington, D.C.: USDA.

Cramer, G.L. and Heid, W.G. (1983) *Grain Marketing Economics* N.Y.: John Wiley & Sons.

Cuperus, G.W., Prickett, C.K., Bloome, P.D. and Pitts, J.T. (1986) Insect populations in aerated and unaerated stored wheat in Oklahoma. *J. Kansas Entomol. Soc*. **59**, 620–27.

Cuperus, G.W., Noyes, R.T., Fargo, W.S., Clary, B.L., Arnold, D.C. and Anderson, K. (1990) Management practices in a high-risk stored-wheat system in Oklahoma. *Amer. Entomol.* **36**, 129–34.

Cuperus, G., Noyes, R.T., Fargo, W.S., Kenkel, P., Criswell, J.T. and Anderson, K. (1993) Reducing pesticide use in wheat postharvest systems. *Cereal Foods World* **38**, 199–203.

Demianyk, C.J, White, N.D.G. and Jayas, D.S. (1997) Rapid detection of rusty grain beetles (Coleoptera: Cucujidae) from wheat samples passing through a mechanical dockage tester. *Can. J. Plant Sci.* **77**, 717–19.

Dent, D. (1995) Implementation of an IPM system. In D. Dent (ed) *Integrated Pest Management* pp. 209–21. London: Chapman & Hall.

Evans, D.E. (1987) Stored products. In A.J. Burn, T.H. Coaker and P.C. Jepson (eds) *Integrated Pest Management* pp. 425–61. London: Academic Press.

Fields, P.G. and Muir, W.E. (1995) Physical control. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products*, pp. 195–221. New York: Marcel Dekker, Inc.

Flinn, P.W. (1998) Temperature effects on efficacy of *Choetospila elegans* (Hymenoptera: Pteromalidae) to suppress *Rhyzopertha dominica* (Coleoptera: Bostrichidae) in stored wheat. *J. Econ. Entomol.* **91**, 320–3.

Flinn, P.W. and Hagstrum, D.W. (1990) Simulations comparing the effectiveness of various stored-grain management practices used to control *Rhyzopertha dominica* (Coleoptera: Bostrichidae). *Environ. Entomol.* **19**, 725–9.

Flinn, P.W. and Hagstrum, D.W. (1994) Field validation of a decision support system for farm-stored grain. *Proc. Sixth International Working Conference on Stored-Product Protection*, pp. 921–4. Wallingford, U.K.: CAB International.

Flinn, P.W. and Hagstrum, D.W. (1995) Simulation model of *Cephalonomia waterstoni* (Hymenoptera: Bethylidae) parasitizing the rusty grain beetle (Coleoptera: Cucujidae). *Environ. Entomol.* **24**, 1608–15.

Flinn, P.W. and Hagstrum, D.W. (1997) Simulation model of low oxygen atmospheres on insect population dynamics in stored grain. *Proc. Int. Conf. Controlled Atmosphere and Fumigation in Stored Products*, pp. 435–42. Nicosia, Cyprus: Printco Ltd.

Flinn P.W., Hagstrum, D.W., Muir, W.E. and Sudayappa, K. (1992) Spatial model for simulating changes in temperatue and insect population dynamics in stored grain. *Environ. Entomol.* **21**, 1351–6.

Flinn, P.W., Hagstrum, D.W. and McGaughey, W.H. (1996) Suppression of beetles in stored wheat by augmentative releases of parasitic wasps. *Environ. Entomol.* **25**, 505–11.

Flinn, P.W., Hagstrum, D.W. and Muir, W.E. (1997) Effects of time of aeration, bin size, and latitude on insect populations in stored wheat: a simulation study. *J. Econ. Entomol*. **90**, 646–51.

Flint, M.L. and van den Bosch, R. (1981) *Introduction to Integrated Pest Management*. New York: Plenum Press.

Frisbie, R.B. and McWhorter, G.M. (1986) Implementing a statewide pest management program for Texas, U.S.A. In J. Palti and R. Ausher (eds) *Advisory Work in Crop Pest and Disease Management*, pp. 234–62. New York: Springer-Verlag.

Fumigation Service and Supply, Inc. (1996) Fumigants and pheromones. *Summer* **42**, 8.

Gittinger, J.P. (1982) *Economic Analysis of Agricultural Projects*. Baltimore: John Hopkins University Press

Glass, E.H (1975) *Integrated Pest Management: Rationale, Potential, Needs and Implementation.* Special Publ. 75-2, College Park, Maryland: Entomological Society of America.

Graebner, L.D., Moreno, D.S. and Baritelle, J.L. (1984) The Fillmore citrus protective district: a success story in integrated pest management. *Bull. Entomol. Soc. Amer*. **30**, 27–33.

Grain Elevator and Processing Society (1995) Japan to reduce maximum dockage in U.S. wheat purchases *IN-GRAIN* **15**, 7.

Gundu Rao, H.R. and Wilbur, D.A. (1972) Loss of wheat weight from feeding of lesser grain borer. *J. Kansas Entomol. Soc.* **45**, 238–41.

Hagstrum, D.W. (1987) Seasonal variation of stored wheat environment and insect populations. *Environ. Entomol*. **16**, 77–83.

Hagstrum, D.W. (1989) Infestation by *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) of newly harvested wheat stored on three Kansas farms. *J. Econ. Entomol*. **82**, 655–9.

Hagstrum, D.W. (1994) Field monitoring and prediction of stored-grain insect populations. *Postharvest News and Information* **5**, 39N–45N.

Hagstrum, D.W. (1995) Ecology of insect pests of stored wheat. *Stored Product Management*, pp. 211–14. Oklahoma State Univ. Coop. Ext. Serv. Circ. E-912.

Hagstrum, D.W. (1996) Monitoring and predicting population growth of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) over a range of environmental conditions. *Environ. Entomol*. **25**, 1354–9.

Hagstrum, D.W. and Flinn, P.W. (1990) Simulations comparing insect species differences in response to wheat storage conditions and management practices. *J. Econ. Entomol*. **83**, 2469–75.

Hagstrum, D.W. and Flinn, P.W. (1992) Integrated pest management of stored-grain insects In D.B. Sauer (ed) *Storage of Cereal Grains and Their Products*, pp. 535–62. St. Paul, Minnesota: Amer. Assoc. Cereal Chem.

Hagstrum, D.W. and Flinn, P.W. (1994) Survival of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) in stored wheat under fall and winter temperature conditions. *Environ. Entomol*. **23**, 390–95.

Hagstrum, D.W. and Flinn, P.W. (1995) Integrated pest management. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products* pp. 399–408. New York: Marcel Dekker.

Hagstrum, D.W. and Heid Jr., W.G. (1988) U.S. wheat-marketing system: An insect ecosystem. *Bull. Entomol. Soc. Am.* **34**, 33–6.

Hagstrum, D.W. and Throne, J.E. (1989) Predictability of stored-wheat insect population trends from life history traits. *Environ. Entomol*. **18**, 660–4.

Hagstrum, D., Flinn, P. and Fargo, S. (1995) How to sample grain for insects. *Stored Product Management* pp. 65–9. Oklahoma State Univ. Coop. Ext. Serv. Circ. E-912.

Hagstrum, D.W., Flinn, P.W. and Howard, R.W. (1995) Ecology. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products* pp. 71–134. New York: Marcel Dekker.

Hagstrum, D.W., Flinn, P.W. and Shuman, D. (1996) Automated monitoring using acoustical sensors for insects in farm-stored wheat. *J. Econ. Entomol*. **89**, 211–17.

Hagstrum, D.W., Subramanyam, Bh. and Flinn, P.W. (1997) Nonlinearity of a generic variance-mean equation for stored grain insect sampling data. *Environ. Entomol*. **26**, 1213–23.

Hagstrum, D.W., Flinn, P.W. and Subramanyam, Bh. (1998) Predicting insect density from probe trap catch in farm-stored wheat. *J. Stored Prod. Res*. **34**, 251–62.

Halderson, J.L. (1985) Results of a grain storage study in Idaho. *Trans. ASAE*. **28**, 246–50, 254.

Hall, D.C. (1977) An economic and institutional evaluation of integrated pest management with an empirical investigation of two California crops. EPA 68-01-2982.

Hunter, C.D. (1997) Suppliers of beneficial organisms in North America. Calif Environ. Prot Agency, Department of Pesticide Regulation, Environ. Monitoring and Pest Management Branch, Sacramento, California.

Hutchins, S.H. (1995) Free Enterprise: The only sustainable solution to IPM implementation. *J. Agric. Entomol*. **12**, 211–17.

Industrial Fumigant Company (1996) *IFC Newsletter*. Sept, 8.

Ingemansen, J.A., Reeves, D.L. and Walstrom, R.J. (1986) Factors influencing stored-oat insect populations in South Dakota. *J. Econ. Entomol*. **79**, 518–22.

Keever, D.W. and Hamm Jr., L.A. (1996) Descriptive model of phosphine concentration and emission rates during controlled aeration of fumigated tobacco warehouses. *J Entomol. Sci*. **31**, 218–26.

Kenkel, P., Adam, B.D., Cuperus, G.W. and Fargo, W.S. (1991) A risk analysis of insect control strategies in stored wheat. AE #9151, Department of Agric. Econ., Oklahoma State University, Stillwater.

Kenkel, P., Criswell, J.T., Cuperus, G., Noyes, R.T., Anderson, K., Fargo, W.S., Shelton, K., Morrison, W.P. and Adams, B. (1993) Current management practices and impact of pesticide loss in the hard red wheat post-harvest system. Oklahoma Cooperative Extension Service Circular E-930.

Kenkel, P., Criswell, J.T., Cuperus, G.W., Noyes, R.T., Anderson, K. and Fargo, W.S. (1994a) Stored product integrated pest management. *Food Reviews International* **10**, 177–93.

Kenkel, P., Noyes, R.T., Cuperus, G.W., Criswell, J., Fargo, S. and Anderson, K. (1994b) U.S. stored-wheat pest management practices: Producers, elevator operators, and mills. *Proc. Sixth International Working Conference on Stored-Product Protection* pp. 935–9. Wallingford, U.K.: CAB International.

Kogan, M. (1998) Integrated pest management: Historical perspectives and contemporary developments. *Ann. Rev. Entomol*. **43**, 243–270.

Lambur, M.T., Kazmierczak Jr., R.F. and Rajotte, E.G. (1989) Analysis of private consulting firms in integrated pest management. *Amer. Entomol*. **35**, 5–11.

Longstaff, B.C. and Cornish, P. (1994) PESTMAN: A decision support system for pest management in the Australian central grain-handling system. *AI Appl*. **8**, 13–23.

Mahmood, T., Ahmad, M.S. and Ahmad, H. (1996) Dispersion of stored grain insect pests in a wheat-filled silo. *Intern. J. Pest Management* **42**, 321–4.

Maier, D.E. (1994) Chilled aeration and storage of U.S. crops – A review. *Proc. Sixth International Working Conference on Stored-Product Protection* pp. 300–11. Wallingford, U.K.: CAB International.

Maier, D.E., Zink, D and Mason, L.J. (1997) Chilled aeration of stored wheat. In J.L. Steele and O.K. Chung (eds) *Proc. Intern. Wheat Quality Conference*, pp. 473. Manhattan, Kansas: Grain Industry Alliance.

Mann, D.D., Jayas, D.S., White, N.D.G., Muir, W.E. and Evans, M.S. (1997) A grain storage information system for Canadian farmers and grain storage managers. *Can. Ag. Eng*. **39**, 49–56.

Martin, M.A., Edwards, C.R., Mason, L.J. and Maier, D.E. (1997) Stored wheat IPM practices and pesticide use in key regions of the United States and Canada: 1996. Publ. B752, West Lafayette, Indiana: Purdue Univ.

Myers, J.H., Savoie, A. and van Randen, E. (1998) Eradication and pest management. *Ann. Rev. Entomol*. **43**, 471–91.

National Research Council (1996) *Ecologically Based Pest Management: New Solutions for a New Century*. Washington, D.C.: National Academy Press.

Norton, G.W. and Mullen, J. (1994) Economic evaluation of integrated pest management programs: A literature review. Virginia Coop. Exten. Publ. 448-120.

Noyes, R.T. and Kenkel, P. (1994) Closed-loop fumigation systems in the south-western U. S. *Proc. Sixth International Working Conference on Stored-Product Protection* pp. 335–41. Wallingford, U.K.: CAB International.

Noyes, R.T., Clary, B.L. and Cuperus, G.W. (1991) Maintaining quality of stored grain by aeration. OSU Extension Facts No.1100, Stillwater: Oklahoma State University.

Noyes, R.T., Kenkel, P. and Tate, G. (1995) Closed loop fumigation systems. *Stored Product Management*. Oklahoma Cooperative Extension Service Circular E-912.

Onstad, D.W. (1987) Calculation of economic-injury levels and economic thresholds for pest management. *J. Econ. Entomol*. **80**, 297–303.

Pedersen, J.R. (1992) Insects: Identification, damage and detection. In D.B. Sauer (ed) *Storage of Cereal Grains and Their Products*, pp. 435–89. St. Paul, Minnesota: Amer. Assoc. Cereal Chem.

Peterson, R.K.D. (1996) The status of economic-decision-level development. In L.G. Higley and L.P. Pedigo (eds) *Economic Thresholds for Integrated Pest Management*, pp. 151–78. Lincoln: Univ. Nebraska Press.

Raupp, M.J., Davidson, J.A., Koehler, C.S., Sadof, C.S. and Reichelderfer, K. (1987) Decision-making considerations for aesthetic damage caused by pests. *Bull. Entomol. Soc. Amer*. **34**, 27–32.

Reed, C. (1992) Development of storage techniques: A historical perspective. In D.B. Sauer (ed) *Storage of Cereal Grains and Their Products*, pp. 143–56. St. Paul, Minnesota: Amer. Assoc. Cereal Chem.

Reed, C. and Harner, J. (1998). Thermostatically controlled aeration for insect control in stored hard red winter wheat. *Appl. Eng. Agric* **14**, 501–5

Reed, C. and Pedersen, J. (1987) Farm-stored wheat in Kansas: Facilities, conditions, pest control, and cost comparisons. *Agricultural Experiment Station Bulletin 652*, Manhattan: Kansas State University.

Reed, C. and Worman, F. (1993) Quality maintenance and marketing of wheat stored on farms and in elevators in Kansas: Description, techniques, and innovations. *Agricultural Experiment Station Bulletin 660*, Manhattan: Kansas State University.

Reed, C., Wright, V.F, Pedersen, J.R. and Anderson, K. (1989) Effects of insect infestation of farm-stored wheat on its sale price at country and terminal elevators. *J. Econ. Entomol*. **82**, 1254–61.

Reed, C., Anderson, K., Brockschmidt, J., Wright, V and Pedersen, J. (1990) Cost and effectiveness of chemical insect control measures in farm-stored Kansas wheat. *J. Kansas Entomol. Soc*. **63**, 351–60.

Reed, C., Pedersen, J.R. and Cuperus, G.W. (1993) Efficacy and cost effectiveness of grain protectants applied to farm-stored wheat at harvest and later. *J. Econ. Entomol.* **86**, 1590–8

Shuman, D., Coffelt, J.A. and Weaver, D.K. (1996) A computer-based electronic fall-through probe insect counter for monitoring infestations in stored products. *Trans. ASAE* **39**, 1773–80.

Smith, L.B. (1985) Insect infestation in grain loaded in railroad cars at primary elevators in southern Manitoba, Canada. *J. Econ. Entomol*. **78**, 831–4.

Smith, L.B. and Loschiavo, S.R. (1978) History of an insect infestation in durum wheat during transport and storage in an inland terminal elevator in Canada. *J. Stored Prod. Res*. **14**, 169–80.

Snelson, J.T. (1987) *Grain Protectants*. Australian Center International Agricultural Research Monograph No.3, Melbourne: Ruskin Press.

Stephens, D.G. (1997) Effect of changing global marketing systems upon wheat quality. In J.L. Steele and O.K. Chung (eds) *Proc. Intern. Wheat Quality Conference* pp. 305–10. Manhattan, Kansas: Grain Industry Alliance.

Stern, V.M., Smith, R.F., van den Bosch, R. and Hagen, K.S. (1959) The integrated control concept. *Hilgardia* **29**, 81–101.

Stone, J.D. and Pedigo, L.P. (1972) Development and economic-injury level of the green cloverworm on soybean in Iowa. *J. Econ. Entomol.* **65**, 197–201.

Storey, C.L., Sauer, D.B., Ecker, O. and Fulk, D.W. (1982) Insect infestations in wheat and corn exported from the United States. *J. Econ. Entomol*. **75**, 827–32.

Storey, C.L., Sauer, D.B. and Walker, D. (1983) Insect populations in wheat, corn, and oats stored on the farm. *J. Econ. Entomol*. **76**, 1323–30.

Storey, C.L, Sauer, D.B. and Walker, D. (1984) Present use of pest management practices in wheat, corn, and oats stored on the farm. *J. Econ. Entomol*. **77**, 784–8.

Subramanyam, Bh. and Hagstrum, D.W. (1995a) Sampling. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products*, pp. 135–93. New York: Marcel Dekker, Inc.

Subramanyam, Bh. and Hagstrum, D.W. (1995b) Resistance measurement and management. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products*, pp. 331–97. New York: Marcel Dekker, Inc.

Subramanyam, Bh., Harem, P.K. and Cutkomp, L.K. (1989) Field tests with probe traps for sampling adult insects infesting farm-stored grain. *J. Agric. Entomol*. **6**, 9–21.

Subramanyam, Bh., Hagstrum, D.W., Meagher, R.L., Burkness, E., Hutchinson, W.D. and Naranjo, S.E. (1997) Development and evaluation of sequential sampling plans for *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae) infesting farm-stored wheat. *J. Stored Prod. Res*. **33**, 321–9.

Throne, J.E. (1994) Computer modeling of the population dynamics of stored-product pests. In D.S. Jayas, N.D.G. White and W.E. Muir (eds) *Stored-Grain Ecosystems*, pp. 169–95. New York: Marcel Dekker, Inc.

Vandeman, A., Fernandez-Cornejo, J., Jans, S. and Lin, B.-H. (1994) Adoption of integrated pest management in U.S. agriculture, USDA-ERS, *Agric. Inf. Bull. 707*, Washington, D.C.

Vela-Coiffier, E.L., Fargo, W.S., Bonjour, E.L., Cuperus, G.W. and Warde, W.D. (1997) Immigration of insects into on-farm stored wheat and relationships among trapping methods. *J. Stored Prod. Res*. **33**, 157–66.

White, G.G. (1983) A modified inclined sieve for separation of insects from wheat. *J. Stored Prod. Res*. **19**, 89–91.

White, G.G. (1985) Population dynamics of *Tribolium castaneum* (Herbst) with implications for control strategies in stored wheat. Ph.D. Thesis, University of Queensland, Brisbane, Australia.

White, G.G. (1988) Field estimates of population growth rates of *Tribolium castaneum* (Herbst) and *Rhyzopertha dominica* (F.) (Coleoptera: Tenebrionidae and Bostrichidae) in bulk wheat. *J. Stored Prod. Res*. **24**, 13–22.

White, N.D.G. and Leesch, J. (1995) Chemical control. In Bh. Subramanyam and D.W. Hagstrum (eds) *Integrated Management of Insects in Stored Products*, pp. 287–330. New York: Marcel Dekker, Inc.

Wilkin, D.R. and Mumford, J.D. (1994) Decision support systems for integrated management of stored commodities. *Proc. Sixth International Working Conference on Stored-Product Protection* pp. 879–83. Wallingford, U.K.: CAB International.

Wilkin, D.R., Catchpole, D. and Catchpole, S. (1994) The detection of insects in grain during transit – an assessment of the problem and the development of a practical solution. *Proc. Sixth International Working Conference on Stored-Product Protection*, pp. 463–69. Wallingford, U.K.: CAB International.

Winks, R.G. (1993) The development of Siroflo® in Australia. *Proc. Intern. Conf. Controlled Atmospheres and Fumigation in Grain Storages*, Winnepeg, Canada.

Worman, F., Reed, C., Schurle, B., Duncan, S. and Pedersen, J. (1993) Kansas country elevator wheat storage practices, 1991. *Staff Paper 93–9*, Department of Agricultural Economics, Kansas State University, Manhattan.